

# Cosmo-02

Adler Planetarium  
Chicago, Illinois USA  
September 18-21, 2002

International Workshop on Particle Physics and the Early Universe

Abstract Deadline  
June 15, 2002

Registration Deadline  
July 15, 2002

# Axions

Georg G. Raffelt

Max-Planck-Institut für Physik (München)

## Plenary Speakers:

- A. Albrecht, UC Davis
- A. Buonanno, IAP (Paris)
- M. de Jesus, Lyon
- A. Dolgov, INFN
- K. Enqvist, Helsinki
- W. Fischler, Texas
- W. Freedman, Carnegie Obs.
- G. Fuller, UC San Diego
- R. Gregory, Durham
- D. Gross, ITP
- A. Guth, MIT
- N. Kaloper, Stanford
- M. Kamionkowski, Caltech

## Talks Include:

- R. Kitaura, CITA
- L. Kofman, UC Davis
- L. Krauss, IITA
- M. Lyth, Rutgers
- M. Peloso, Michigan
- R. Schaefer, ITP
- E. Seidel, Penn State
- L. Randall, Harvard
- L. Roszkowski, Lancaster
- N. Seiberg, IAS
- G. Sigl, Paris
- M. Trodden, Princeton
- D. Wands, Portsmouth
- D. Wands, Ohio State

## Local Co-Chairs:

- John Beacom, Fermilab
- Sean Carroll, University of Chicago
- Gary Gates, Adler Planetarium

## Organized by:

Center for Cosmological Physics,  
University of Chicago (Sponsor)

Adler Planetarium (Host)

Fermilab

# The CP Problem of Strong Interactions

Standard QCD Lagrangian contains a CP violating term

Characterizes degenerate QCD ground state ( $\Theta$  vacuum)

Phase of Quark Mass Matrix

$$L_{CP} = -\frac{\alpha_s}{2\pi} \underbrace{(\Theta - \arg \det M_q)}_{0 \leq \Theta \leq 2\pi} \vec{E}_{\text{color}} \cdot \vec{B}_{\text{color}}$$

Induces a neutron electric dipole moment (EDM) much in excess of experimental limits

$$d_n \approx \overline{\Theta} 10^{-16} \text{ ecm} \approx \frac{\overline{\Theta}}{10^2} \mu_n < 10^{-25} \text{ ecm}$$

$\overline{\Theta} < 10^{-9}$  Why so small?

# Dynamical Solution

Peccei & Quinn 1977 - Wilczek 1978 - Weinberg 1978

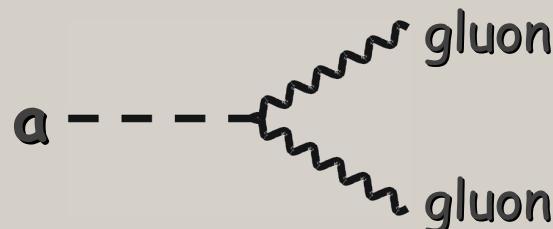
Re-interpret  $\bar{\Theta}$  as  
a dynamical variable  
(scalar field)

$$\bar{\Theta} \rightarrow \frac{a(x)}{f_a}$$

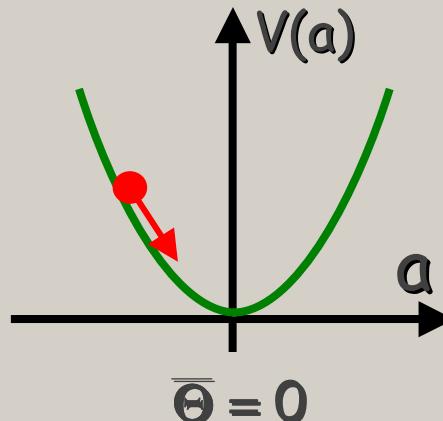
Pseudo-scalar axion field  
Peccei-Quinn scale,  
Axion decay constant

$$L_{CP} = -\frac{\alpha_s}{2\pi} \bar{\Theta} \vec{E}_{color} \cdot \vec{B}_{color}$$

$$-\frac{\alpha_s}{2\pi} \frac{a(x)}{f_a} \vec{E}_{color} \cdot \vec{B}_{color}$$



Axions generically couple to  
gluons and thus mix with  $\pi^0$



Potential (mass term)  
induced by  $L_{CP}$  drives  
 $a(x)$  to CP-conserving  
minimum

**CP-symmetry  
dynamically restored**

$$\left( \begin{array}{l} \text{Axion mass} \\ \& \text{couplings} \end{array} \right) \sim \left( \begin{array}{l} \text{Pion mass} \\ \& \text{couplings} \end{array} \right) \times \frac{f_\pi}{f_a}$$

$f_\pi \approx 93$  MeV  
Pion decay constant

# Windows of Opportunity

## Axions

Solve strong CP problem  
by Peccei-Quinn  
dynamical symmetry restoration

- Cosmic cold dark matter candidate
- Direct detection possible

Search for new physics at  $E \gg \text{TeV}$   
in low-energy experiments  
(Axions Nambu-Goldstone boson of  
spontaneously broken symmetry)

## Alternatives

- Massless up-quark
- Spontaneous CP violation
- Fine tuning

- Supersymmetric particles
- Superheavy particles
- Sterile Neutrinos
- Many others ...  
(but usually not experimentally accessible)

- Neutrino masses (see-saw)
- Proton decay
- Monopoles
- Deviation from Newton's Law  
(e.g. large extra dimensions)

# Axion Production in the Early Universe

Thermalization at  $T < \Lambda_{QCD}$  ?

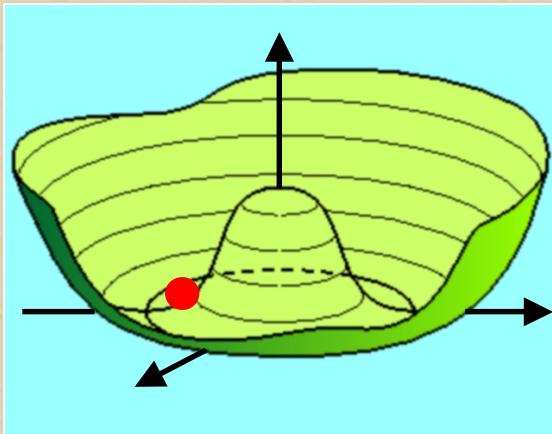
YES

NO for  $f_a > O(10^8 \text{ GeV})$

Thermal relics

$$\Omega_a \propto m_a \propto f_a^{-1}$$

For  $m_a \sim 10 \text{ eV}$   
hot dark matter  
(Excluded by  
astrophysical limits)

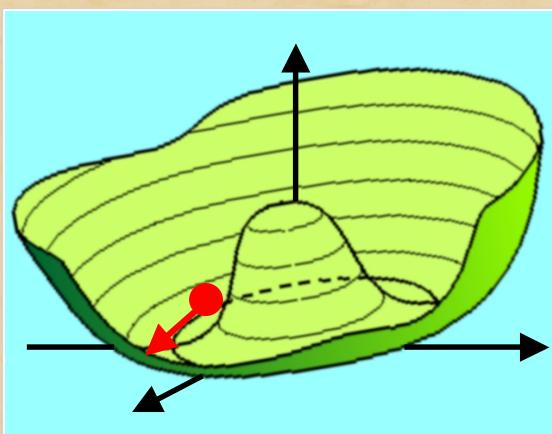


Non-thermal relics from QCD epoch

$$\Omega_a \propto f_a^{1.175} \propto m_a^{-1.175}$$

$T \sim f_a$

- $U_{PQ}(1)$  spontaneously broken
- Higgs field settles in "Mexican hat"



$T \sim \Lambda_{QCD} \ll f_a$

- $U_{PQ}(1)$  explicitly broken by instanton effects
- Mexican hat tilts
- Axions acquire a mass

# Axion Production in the Early Universe

Thermalization at  $T < \Lambda_{QCD}$  ?

YES

NO for  $f_a > O(10^8 \text{ GeV})$

Thermal relics

$$\Omega_a \propto m_a \propto f_a^{-1}$$

Non-thermal relics from QCD epoch

$$\Omega_a \propto f_a^{1.175} \propto m_a^{-1.175}$$

For  $m_a \sim 10 \text{ eV}$   
hot dark matter  
(Excluded by  
astrophysical limits)

For  $m_a \sim 100 \mu\text{eV}$  cold dark matter

Reheating  $T$  after inflation  $\ll f_a$  ?

YES

NO

Homogeneous mode  
oscillates after  
 $T \sim \Lambda_{QCD}$

Cosmic strings of  
broken  $U_{PQ}(1)$  radiate  
long-wavelength axions

$$\Omega_a \propto \bar{\Theta}_{\text{initial}}$$

$\Omega_a$  independent of  
initial conditions

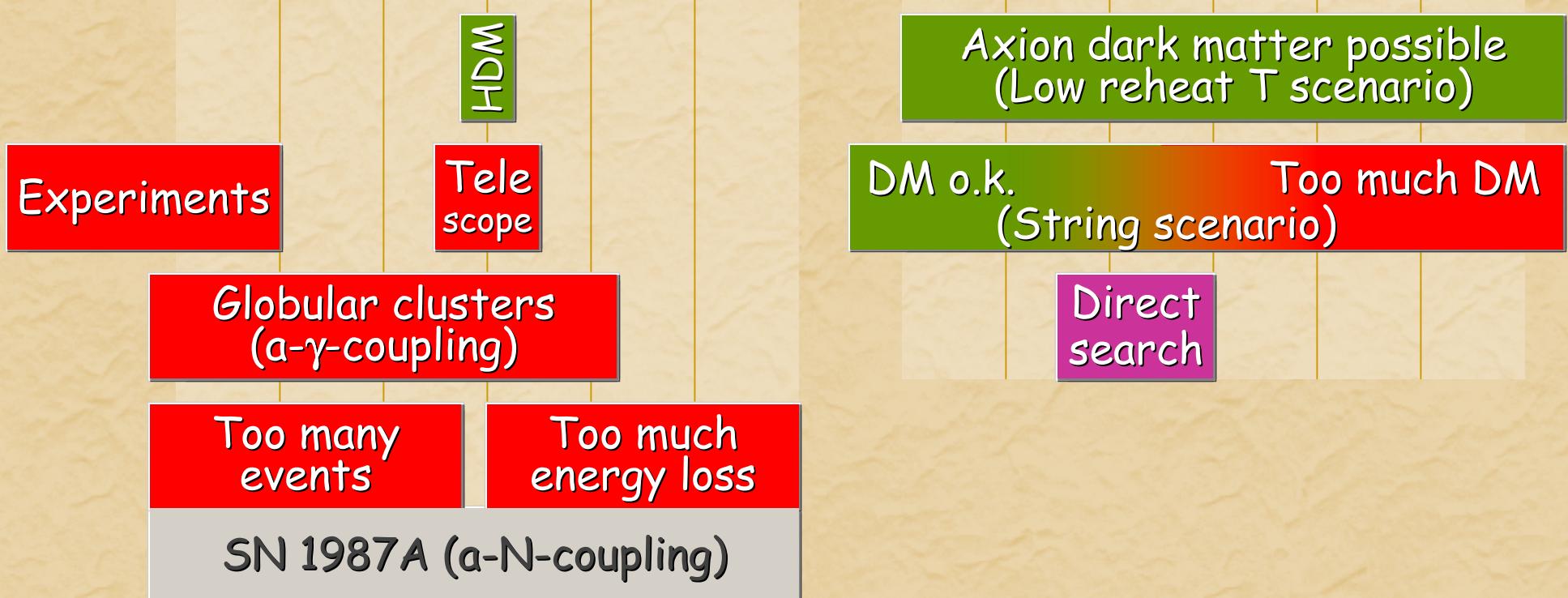
# Astrophysical Axion Bounds

## Stellar Evolution

## Cosmology

$10^3 \quad 10^6 \quad 10^9 \quad 10^{12} \quad [GeV] \quad f_a$

$m_a$  ← keV eV meV μeV



# Experimental Search for Galactic Axions

DM axions

$$m_a = 10\text{--}3000 \mu\text{eV}$$

Velocities in galaxy

$$v_a \approx 10^{-3} c$$

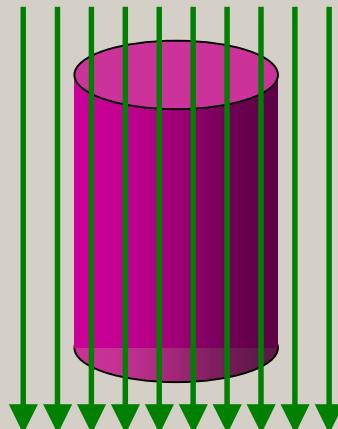
Energies therefore

$$E_a \approx (1 \pm 10^{-6}) m_a$$



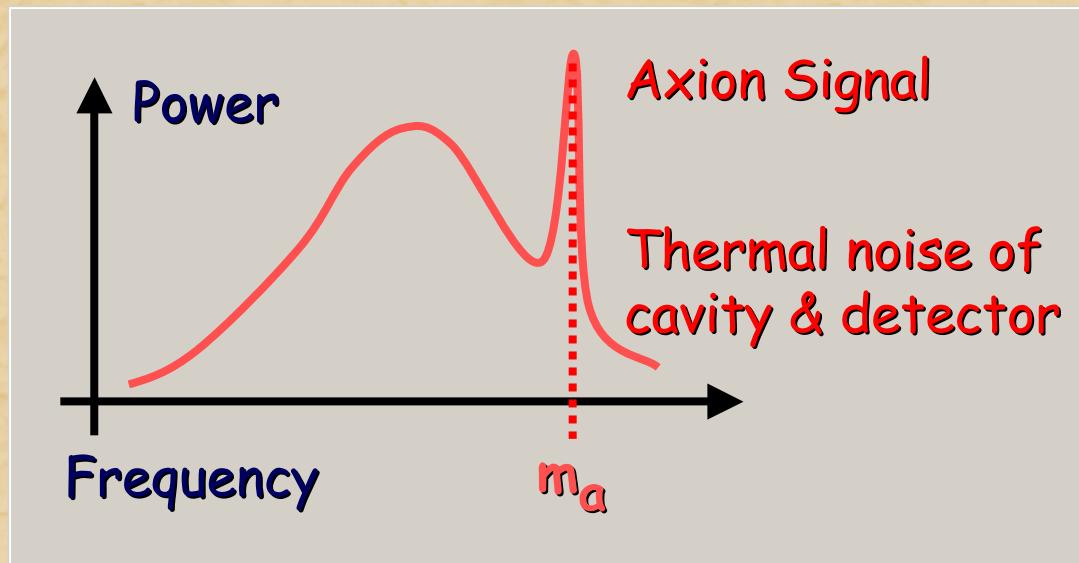
Microwave Energies  
(1 GHz  $\approx 4 \mu\text{eV}$ )

Axion Haloscope (Sikivie 1983)



$$B_{\text{ext}} \approx 8 \text{ Tesla}$$

Microwave  
Resonator  
 $Q \approx 10^5$



Primakoff Conversion

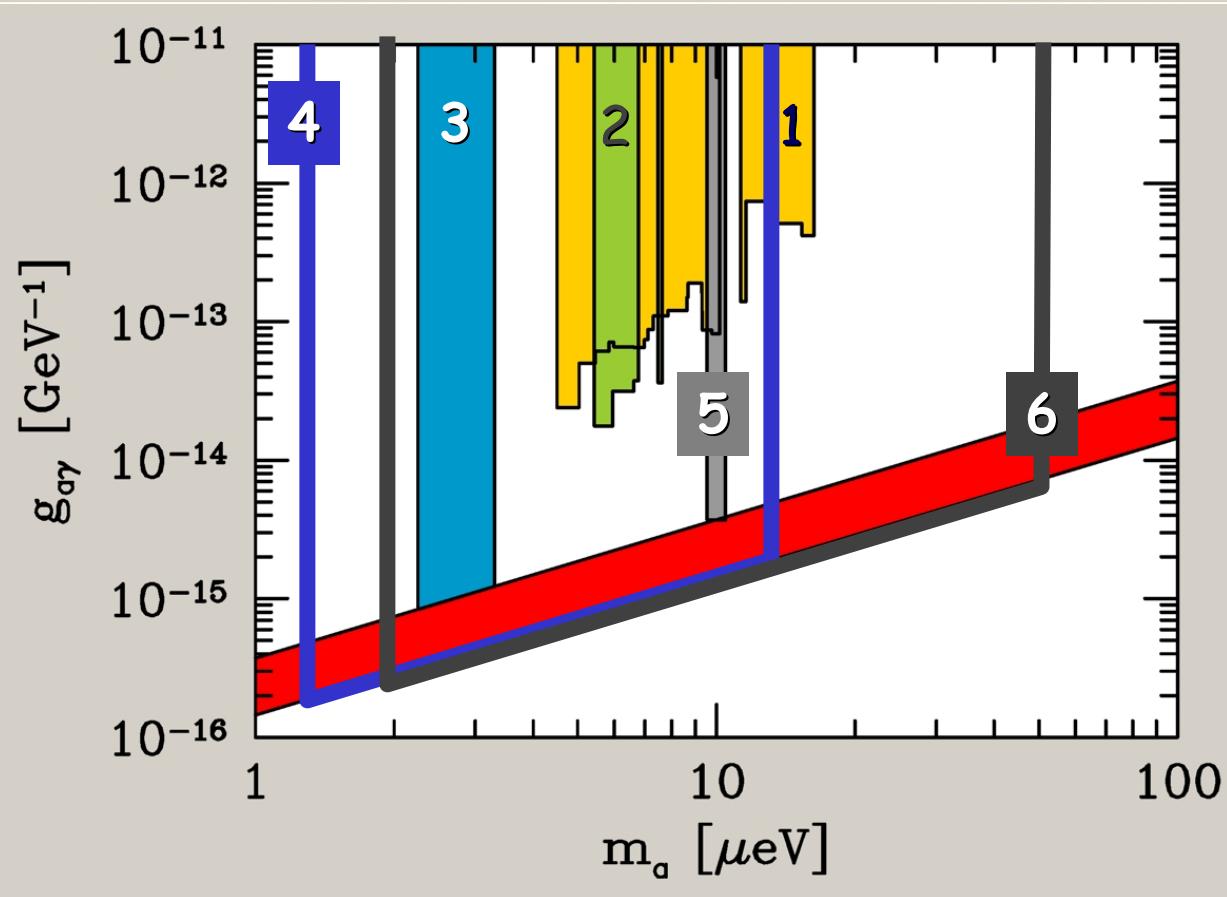


Power of galactic axion signal

$$4 \times 10^{-21} W \frac{V}{0.22 \text{ m}^3} \left( \frac{B}{8.5 \text{ T}} \right)^2 \frac{Q}{10^5} \times \left( \frac{m_a}{2\pi \text{ GHz}} \right) \left( \frac{\rho_a}{5 \times 10^{-25} \text{ g/cm}^3} \right)$$

# Axion Dark Matter Searches

Limits/sensitivities assume axions are the galactic dark matter



1. Rochester-Brookhaven-Fermilab  
PRD 40 (1989) 3153
2. University of Florida  
PRD 42 (1990) 1297
3. US Axion Search (Livermore)  
ApJL 571 (2002) L27
4. ADMX (Livermore)  
Phys Repts 325 (2000) 1
5. CARRACK I (Kyoto)  
preliminary  
hep-ph/0101200
6. CARRACK II (Kyoto)  
hep-ph/0101200

# Axion Dark Matter Searches

Limits/sensitivities as some axions are

galactic dark matter

10<sup>-11</sup>

10<sup>-12</sup>

[ $\Gamma$ ]

$g_{a\gamma}$  [ $G_F$ ]

10<sup>-13</sup>

10<sup>-14</sup>

10<sup>-15</sup>

1

$m_a$

Steve Asztalos:  
The U.S. dark matter axion search  
Thursday, 2:50 p.m.

1. Rochester Brookhaven-  
(1989) 3153

2. LBL

3. 27

4. Livermore)  
Phys 325 (2000) 1

5. CARRACK I (Kyoto)  
prelim.  
hep-ph/0101200

6. CARRACK II (Kyoto)  
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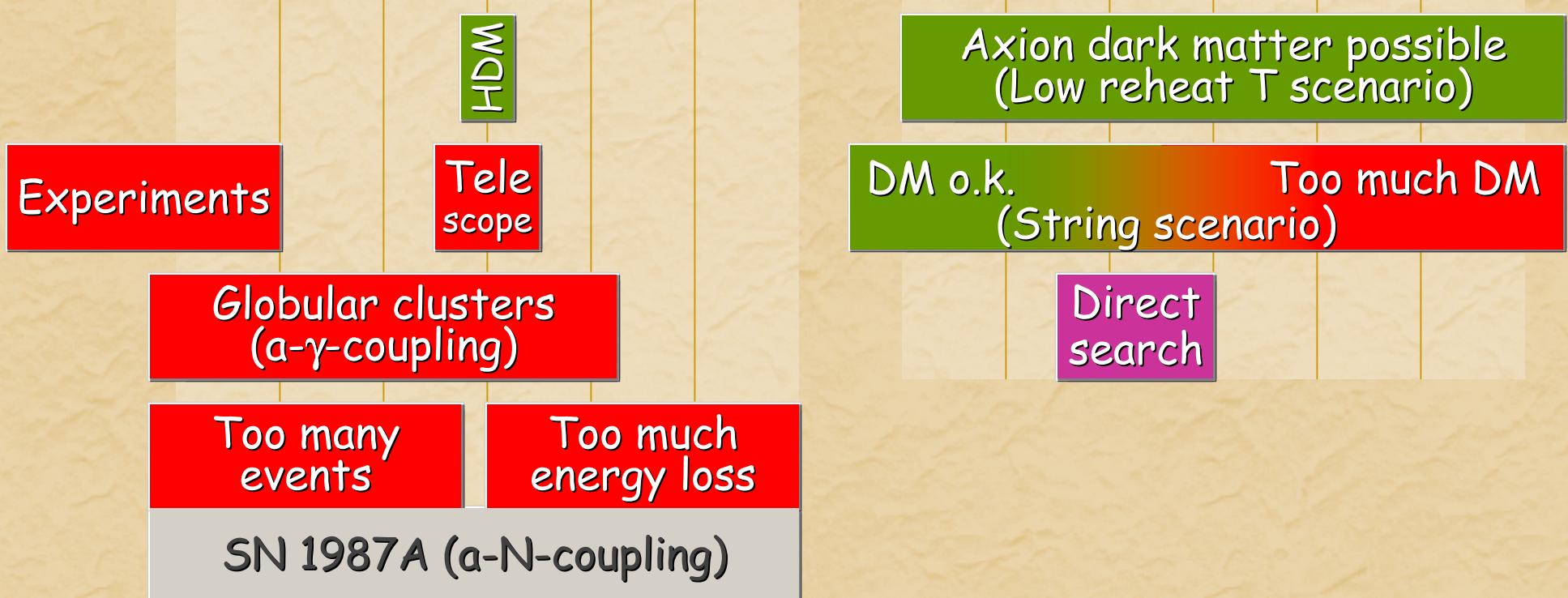
# Astrophysical Axion Bounds

## Stellar Evolution

## Cosmology

$10^3 \quad 10^6 \quad 10^9 \quad 10^{12} \quad [GeV] \quad f_a$

$m_a$  ← keV eV meV μeV



# Axinos as Dark Matter

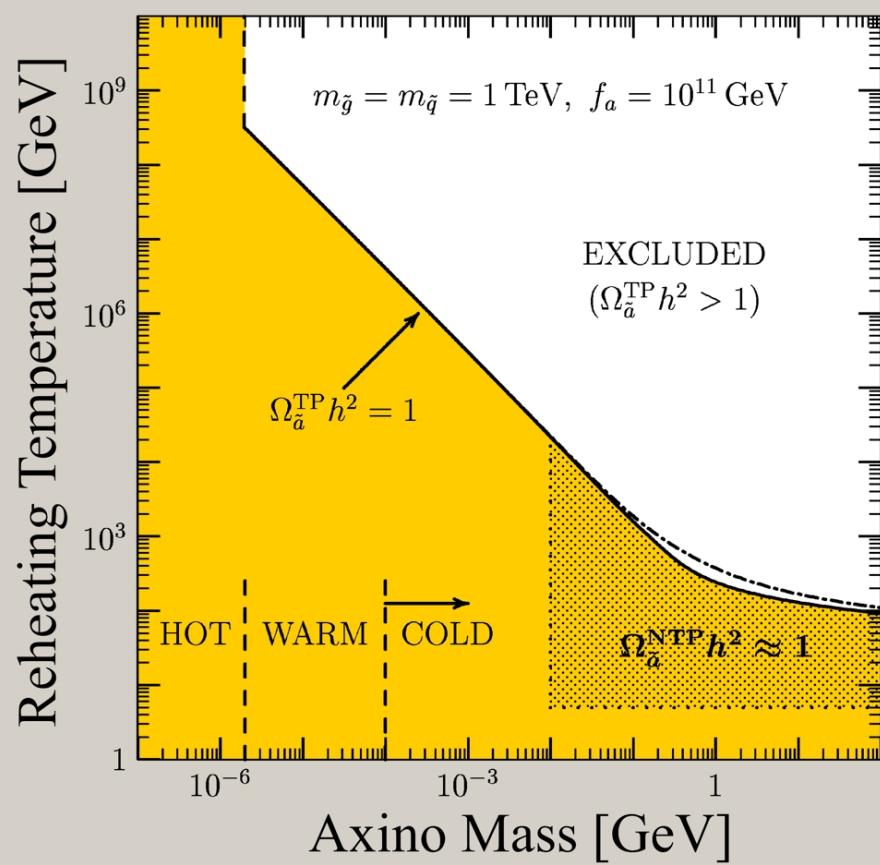
Gauge hierarchy problem solved by supersymmetry

LSP good CDM candidate

Strong CP problem solved by Peccei-Quinn mechanism

Axion good CDM candidate

Axino also good and generic CDM candidate



- For Peccei-Quinn scale in allowed range and a low reheating T after inflation, thermal processes and decay of NLSP can produce CDM axinos
- No obvious experimental search possible

- Covi, Kim & Roszkowski  
PRL 82 (1999) 4180
- Covi, Kim, Kim & Roszkowski  
JHEP 0105 (2001)
- Covi, Roszkowski & Small  
[hep-ph/0206119](https://arxiv.org/abs/hep-ph/0206119)

# Axinos as Dark Matter

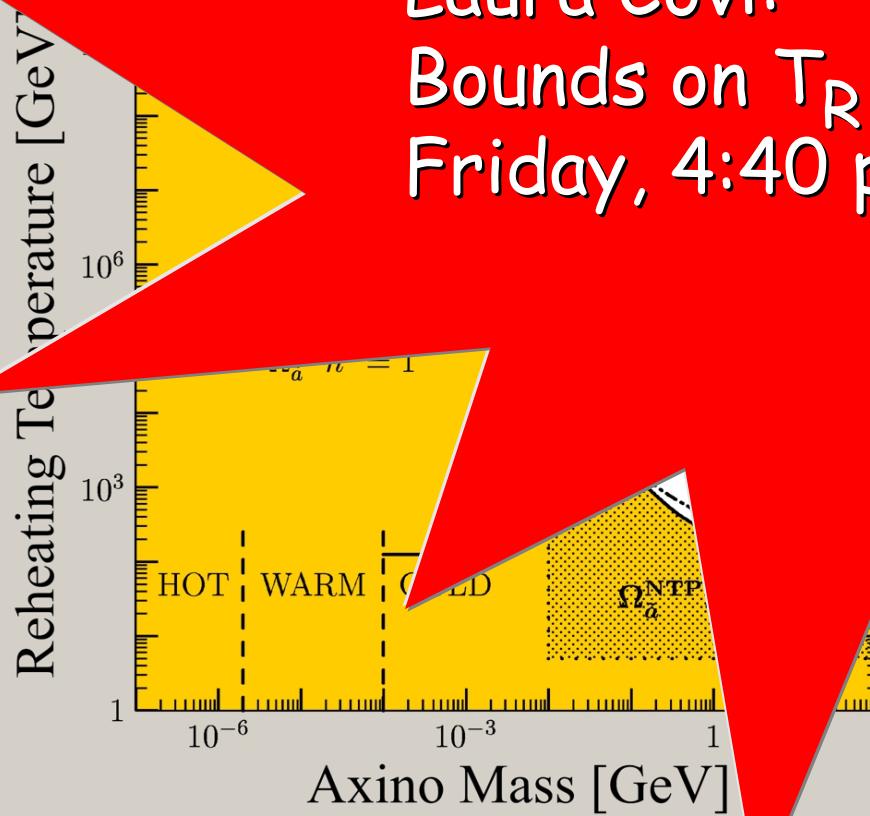
Gauge hierarchy problem solved by supersymmetry

LS

M candidate

CP problem solved by Seesaw-Quinn mechanism

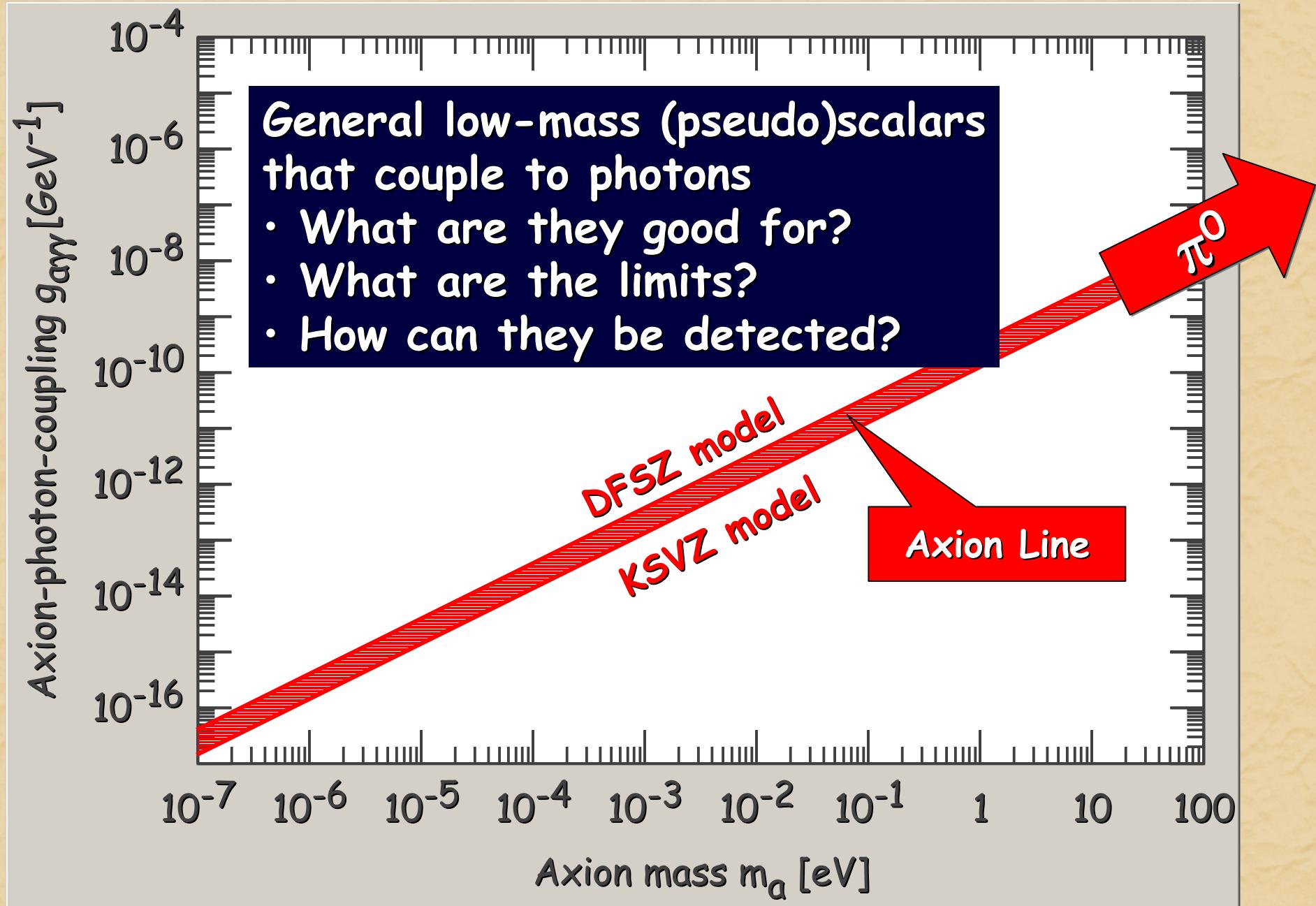
candidate



Laura Covi:  
Bounds on  $T_R$  from axino CDM  
Friday, 4:40 p.m.

- Proton decay  
• Covell, Roszkowski & Kim (1999) 4180
- Covell, Roszkowski & Kim & Roszkowski (2001) JHEP 05 (2001)
- Covell, Roszkowski & Small (2002) hep-ph/0206119

# Axion-Like Particles that Couple to Photons



# Two-Photon Coupling and its Consequences

## Particles with two-photon vertex:

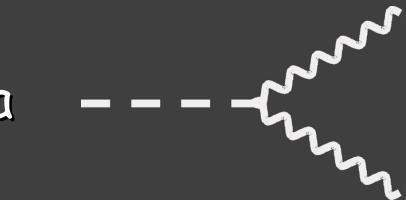
- Neutral pions ( $\pi^0$ ), Gravitons
  - Axions (a) and similar hypothetical particles

$$L_{\alpha\gamma} = g_{\alpha\gamma} \vec{E} \cdot \vec{B} a - \dots$$

# Two-photon decay

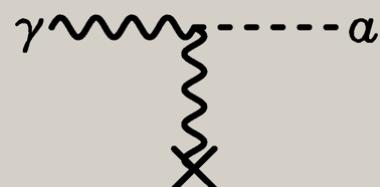
$$\Gamma_{\text{ay}} = \frac{g_{\text{ay}}^2 m_{\text{ay}}}{64\pi}$$

# Photon Coalescence



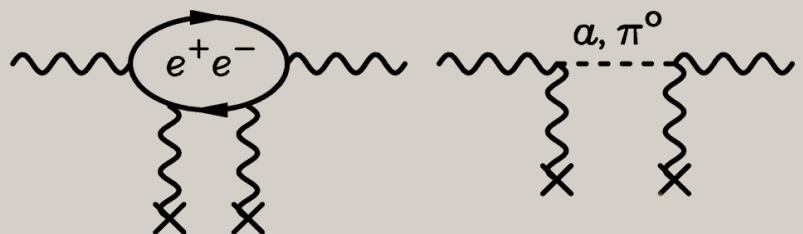
# Primakoff Effect

## Conversion of photons into pions, gravitons or axions, or the reverse

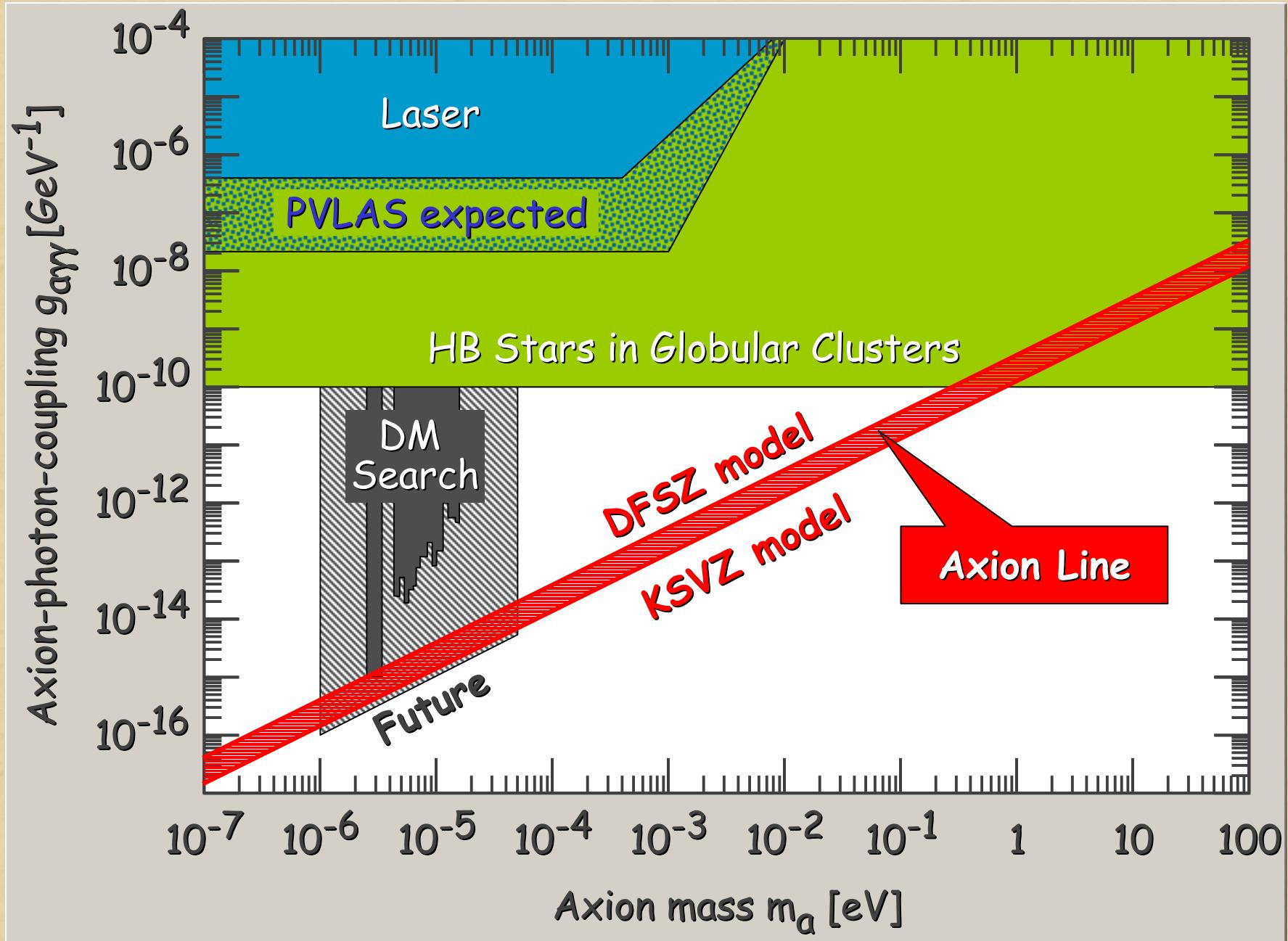


# Magnetically induced vacuum birefringence

## In addition to QED Cotton-Mouton-effect



# Limits on Axion-Photon-Coupling



# Dimming of Supernovae without Cosmic Acceleration

Csáki, Kaloper & Terning

PRL 88 (2002) 161302, PLB 535 (2002) 33

Erlich & Grojean  
hep-ph/0111335

Deffayet, Harari, Uzan  
& Zaldarriaga, hep-ph/0112118

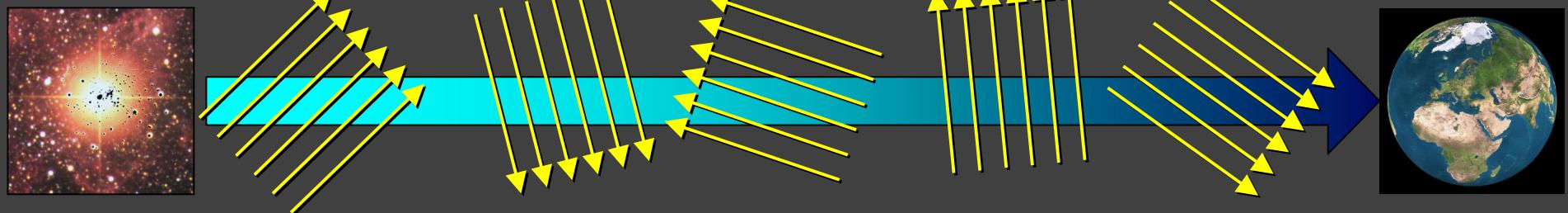
Mörtsell, Bergström & Goobar

astro-ph/0202153

Christensson & Fairbairn  
astro-ph/0207525

Axion-photon-oscillations in intergalactic B-field domains dim photon flux

- Effect grows linearly with distance
- Saturates at equipartition between photons and axions (unlike grey dust)



Mixing matrix

$$\frac{1}{2\omega} \begin{pmatrix} \omega_{pl}^2 & g_{ay} B \omega \\ g_{ay} B \omega & m_a^2 \end{pmatrix} = \begin{pmatrix} 10.8 n_e \omega^{-1} & 0.15 g_{ay}^2 B \\ 0.15 g_{ay}^2 B & 7.8 \times 10^{-4} m_a^2 \omega^{-1} \end{pmatrix} \text{Mpc}^{-1}$$

Domain size  $\sim 1$  Mpc  
Field strength  $\sim 1$  nG  
 $a\gamma$ -coupling  $\sim 10^{-10}$  GeV $^{-1}$   
Axion mass  $< 10^{-16}$  eV

Photon energy  $\sim 1$  eV  
Electron density  
 $\sim 10^{-7}$  cm $^{-3}$   
(average baryon density)

Chromaticity depends  
sensitively on assumed  
values and distribution  
of  $n_e$  and  $B$

# Dimming of Supernovae without Cosmic Acceleration

Bráki, Kaloper & Terning  
PRL 88 (2002) 161302, PLB 533 (2002) 33

Erlich & Srednicki | Deffayet & Zaldarriaga | Uzan & Uzan  
hep-ph/0202153

Axion-photon  
♦ Effect on photon flux

Ell, Bergström & Goobar  
hep-ph/0202153

Christensen & Fairbairn  
arXiv:astro-ph/0207525

Photon flux

John Terning:  
Dimming Supernovae via Axions  
Thursday, 4:00 p.m.

Mixing matrix

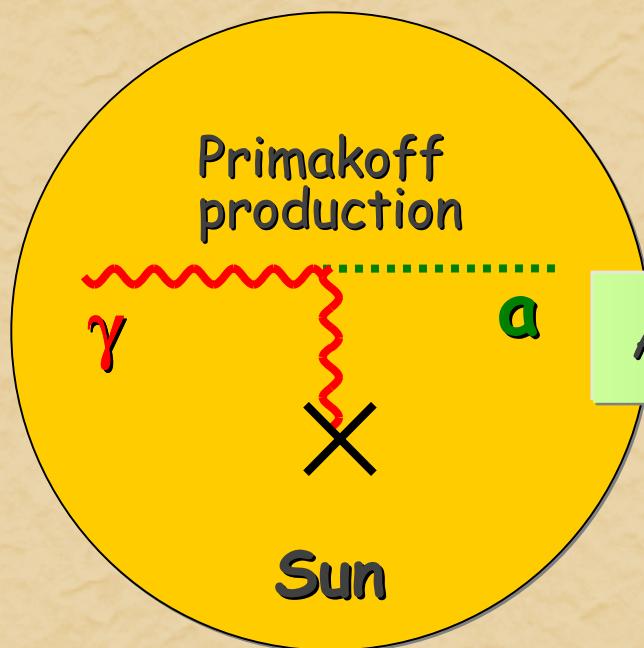
Domain size  $\sim 1 \text{ mpc}$   
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Axion mass  $< 10^{-16} \text{ eV}$

Energy  $\sim$   
on density  
 $\text{cm}^{-3}$   
(average baryon density)

$7.8 \times 10^{-10} \text{ GeV}^{-1} \text{ cm}^{-3} \text{ Mpc}^{-1}$

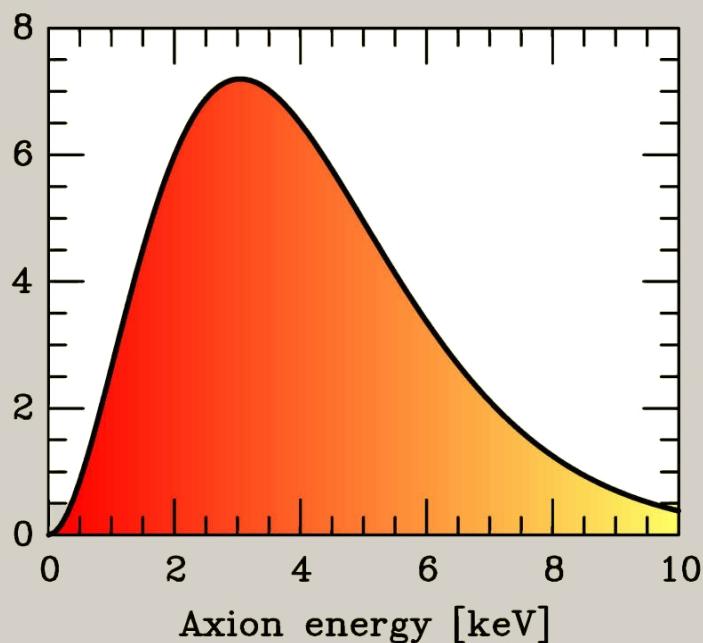
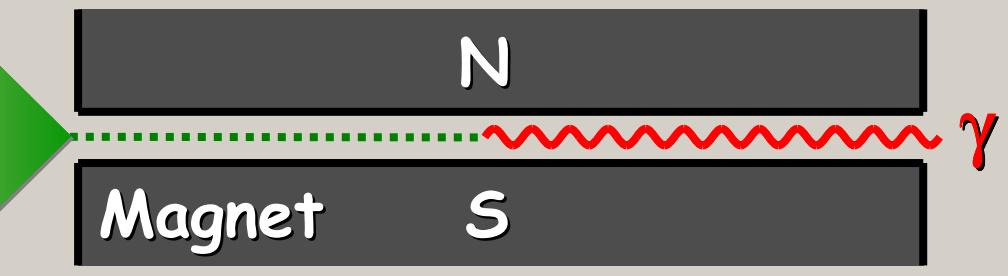
Chromaticity depends  
sensitively on assumed  
values and distribution  
of  $n_e$  and  $B$

# Search for Solar Axions



Axion Helioscope (Sikivie 1983)

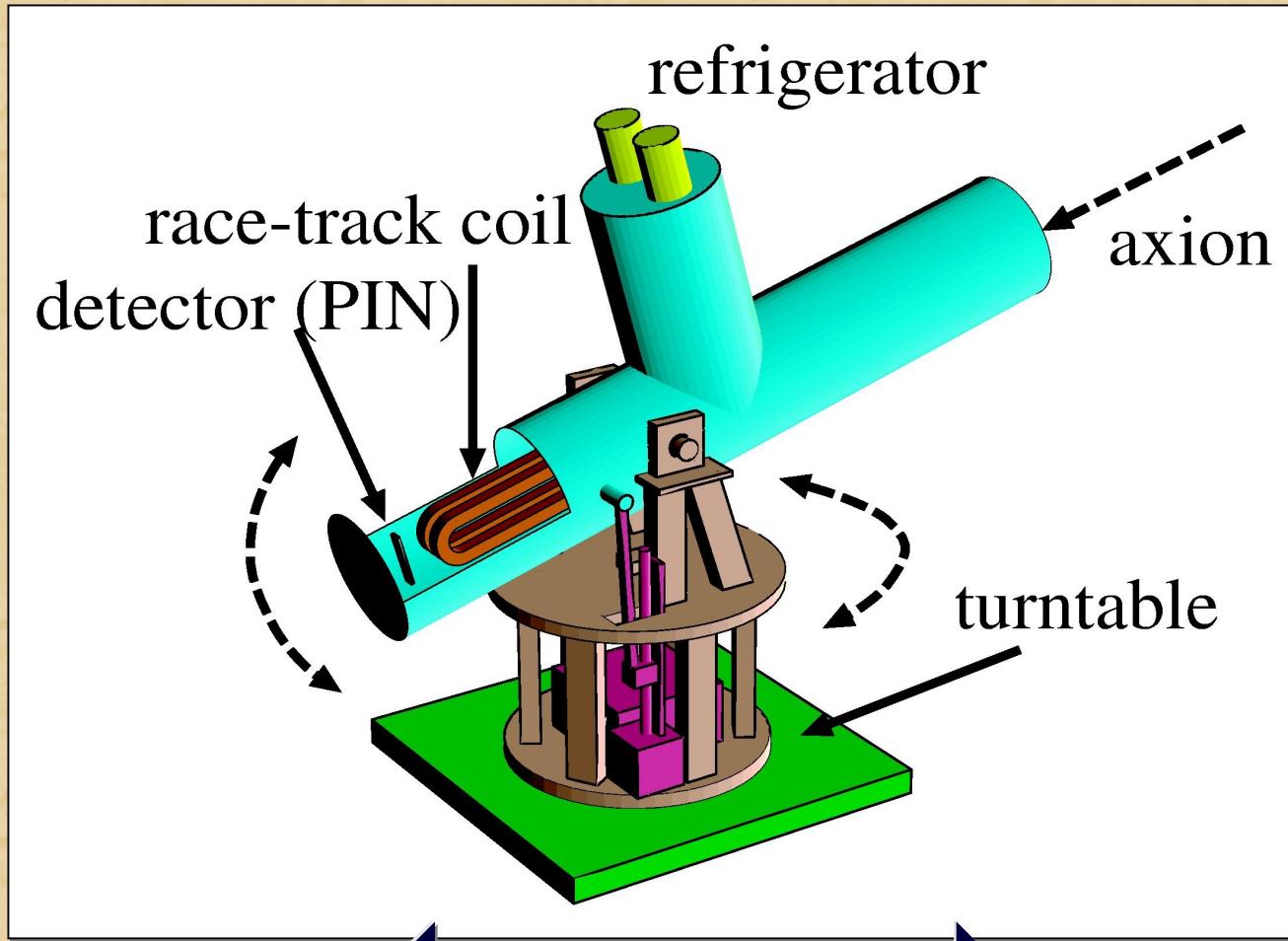
Axion-Photon-Oscillation



- Tokyo Axion Helioscope  
(Results since 1998)
- CERN Axion Solar Telescope (CAST)  
(in preparation)

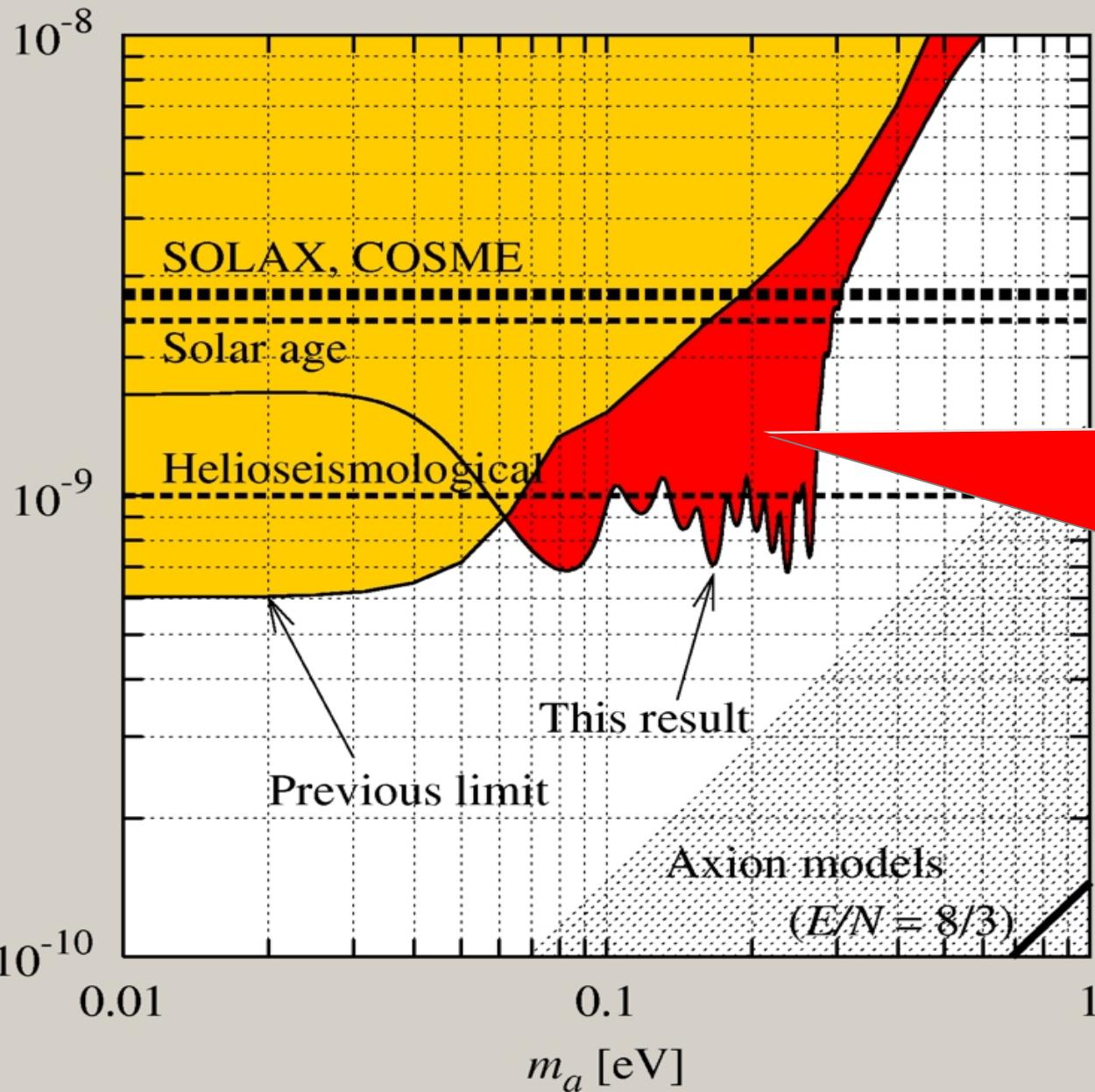
Alternative Technique:  
Bragg conversion in crystal  
Experimental limits on solar axion flux  
from dark-matter experiments  
(SOLAX, COSME, DAMA, ...)

# Tokyo Axion Helioscope



S.Moriyama, M.Minowa, T.Namba, Y.Inoue, Y.Takasu & A.Yamamoto,  
PLB 434 (1998) 147

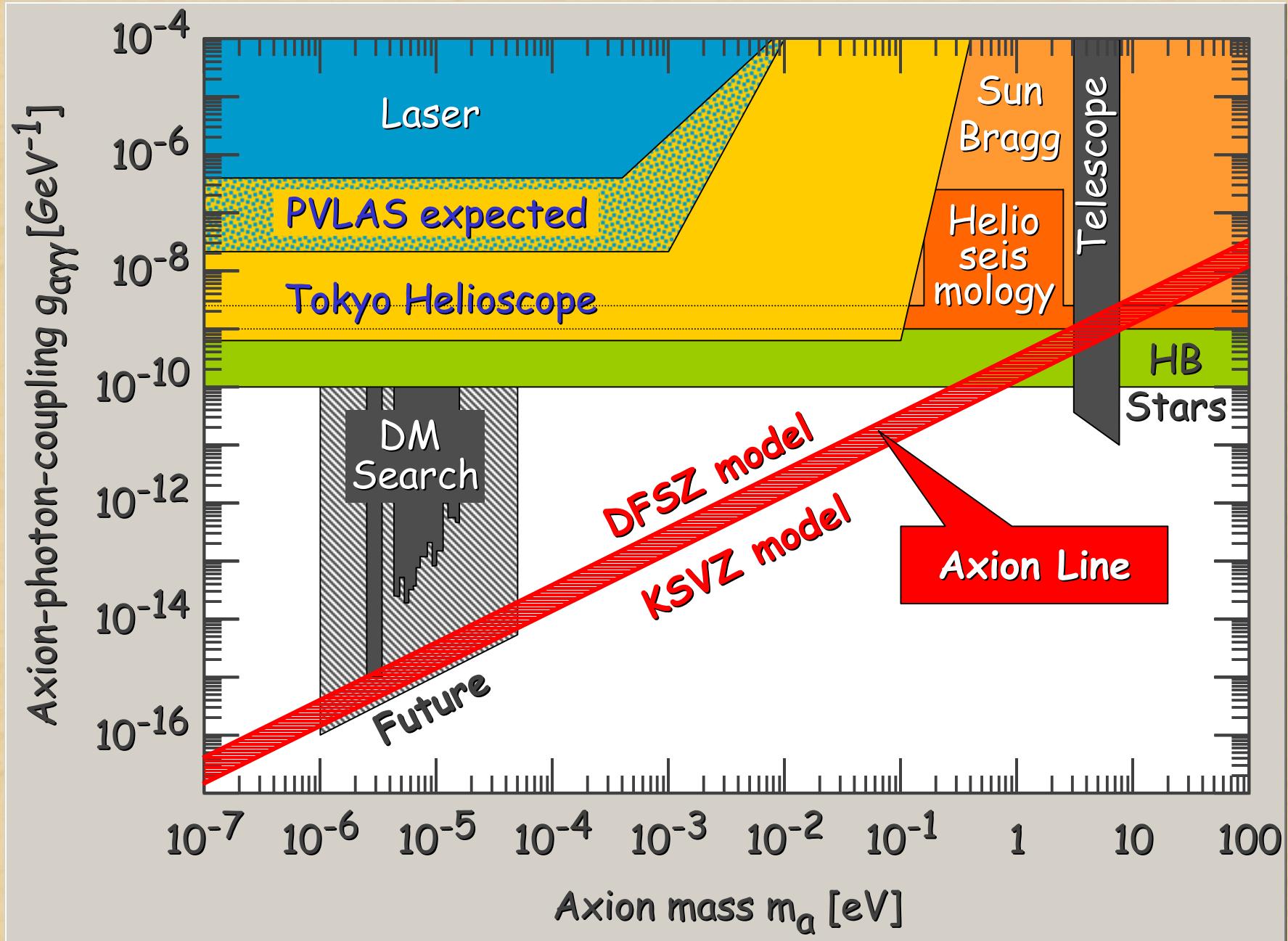
# New Limits from Tokyo Axion Helioscope



Y. Inoue et al.,  
astro-ph/0204388

Axion-photon  
transition region  
filled with  
pressurized gas  
to give photons  
an effective mass  
(avoid momentum  
mismatch)

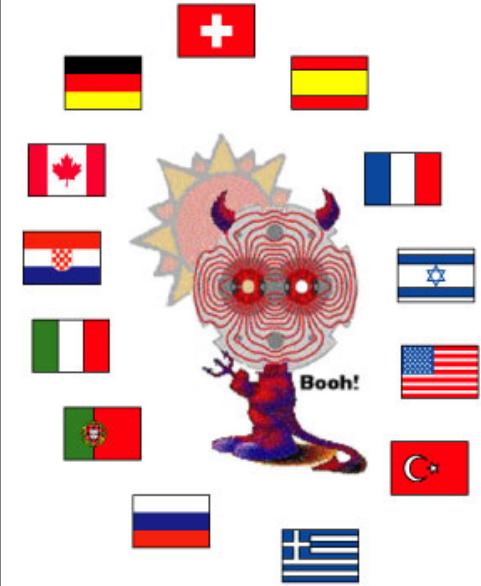
# Limits on Axion-Photon-Coupling



# CERN Axion Solar Telescope (CAST)

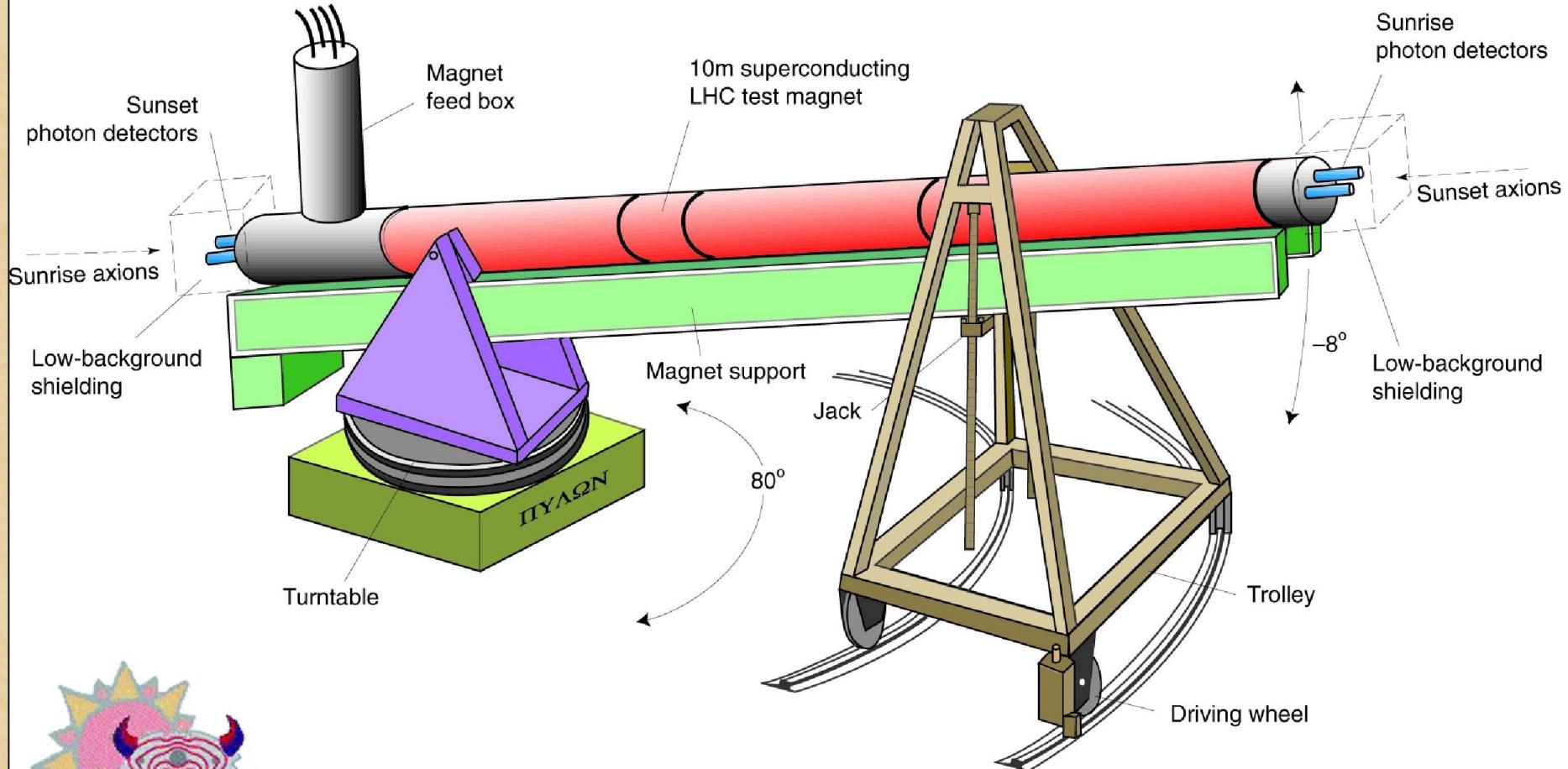
Solar axion search at CERN using a decommissioned LHC test magnet

Formerly  
Solar  
Axion  
Telescopic  
ANTenna



E.Arik, D.Autiero, F.Avignone, K.Barth, S.Bowyer, H.Bräuninger, R.Brodzinski,  
J.Carmona, F.Cataneo, S.Cebrian, G.Celebi, S.Cetin, J.Collar, R.Creswick,  
M.Delattre, A.Delbart, R.de Oliveira, L.di Lella, N.Erduran, G.Fanourakis,  
H.Farach, C.Fiorini, E.Garcia, T.Geralis, I.Giomataris, T.Girard, S.Gninenko,  
N.Goloubev, M.Hasinoff, D.Hoffmann, I.Irastorza, J.Jacoby, K.Jakovcic,  
M.Knopf, M.Krcmar, Z.Krecak, A.Ljubicic, A.Longoni, G.Lutz, G.Luzon, A.Mailov,  
V.Matveev, H.Miley, A.Morales, J.Morales, M.Mutterer, S.Nussinov, A.Ortiz de  
Solorzano, W.Pitts, A.Placci, J.Puimedon, G.Raffelt, H.Riege, M.Sampietro,  
M.Sarsa, M.Stipcevic, C.Thomas, R.Thompson, P.Valko, J.Villar, B.Vullierme,  
L.Walckiers, W.Wilcox, K.Zachariadou, K.Zioutas

# Horizontally Moving Platform



**Cern Axion Solar Telescope**

# Recent Picture of CAST (12 August 2002)

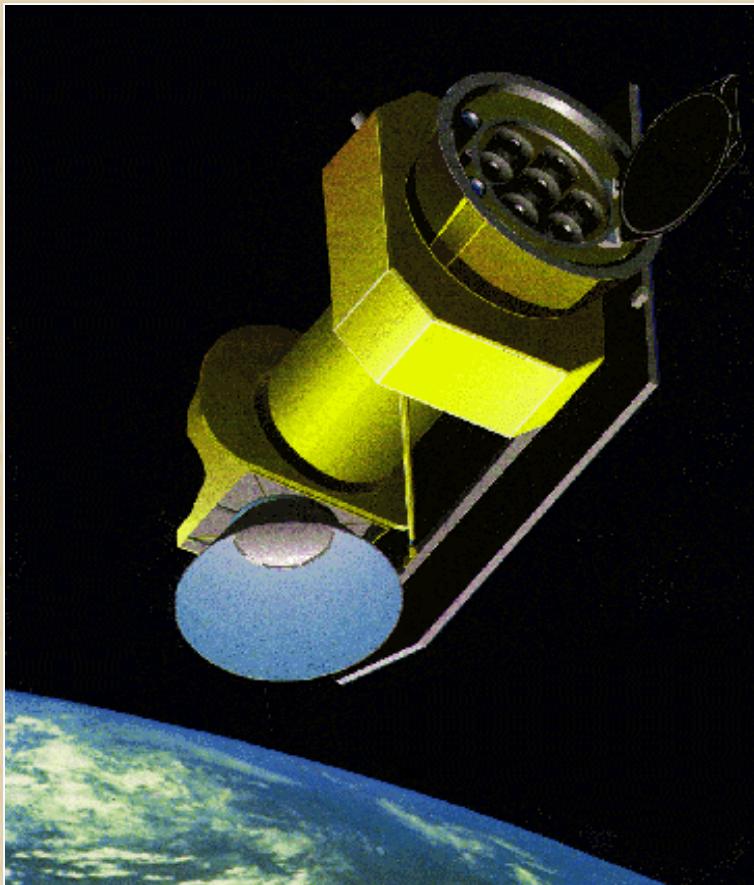


# X-Ray Focussing to Increase Signal-To-Noise

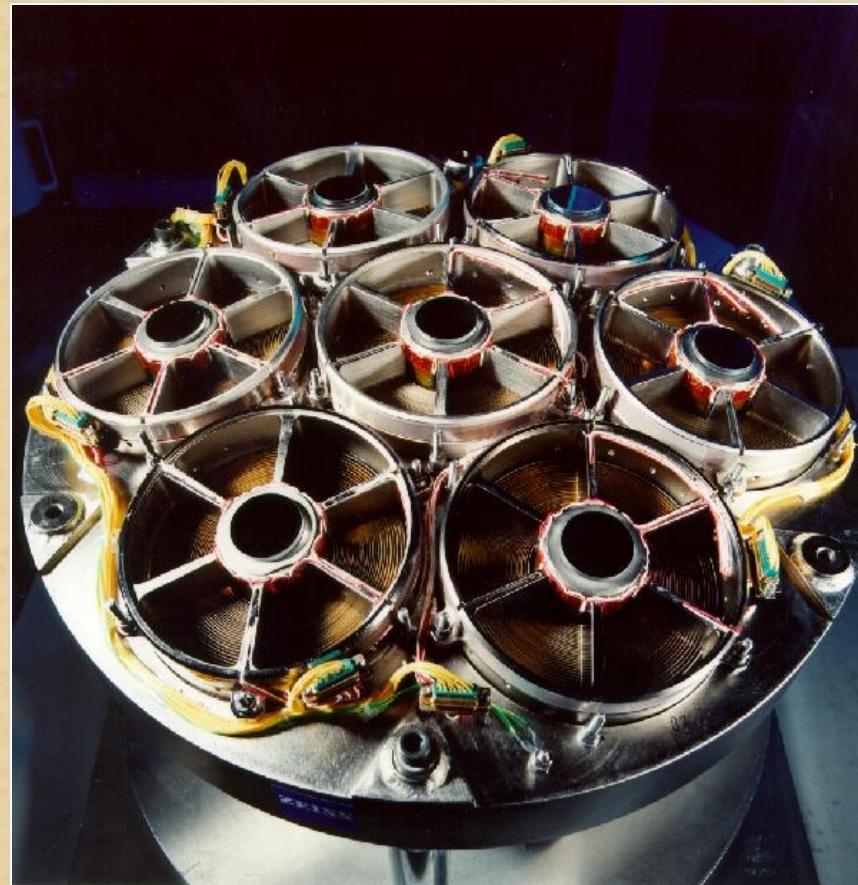
With imaging x-ray mirror, solar image  $\sim 1 \text{ mm}^2$   
compared with  $14 \text{ cm}^2$  magnet bore



Vast background suppression

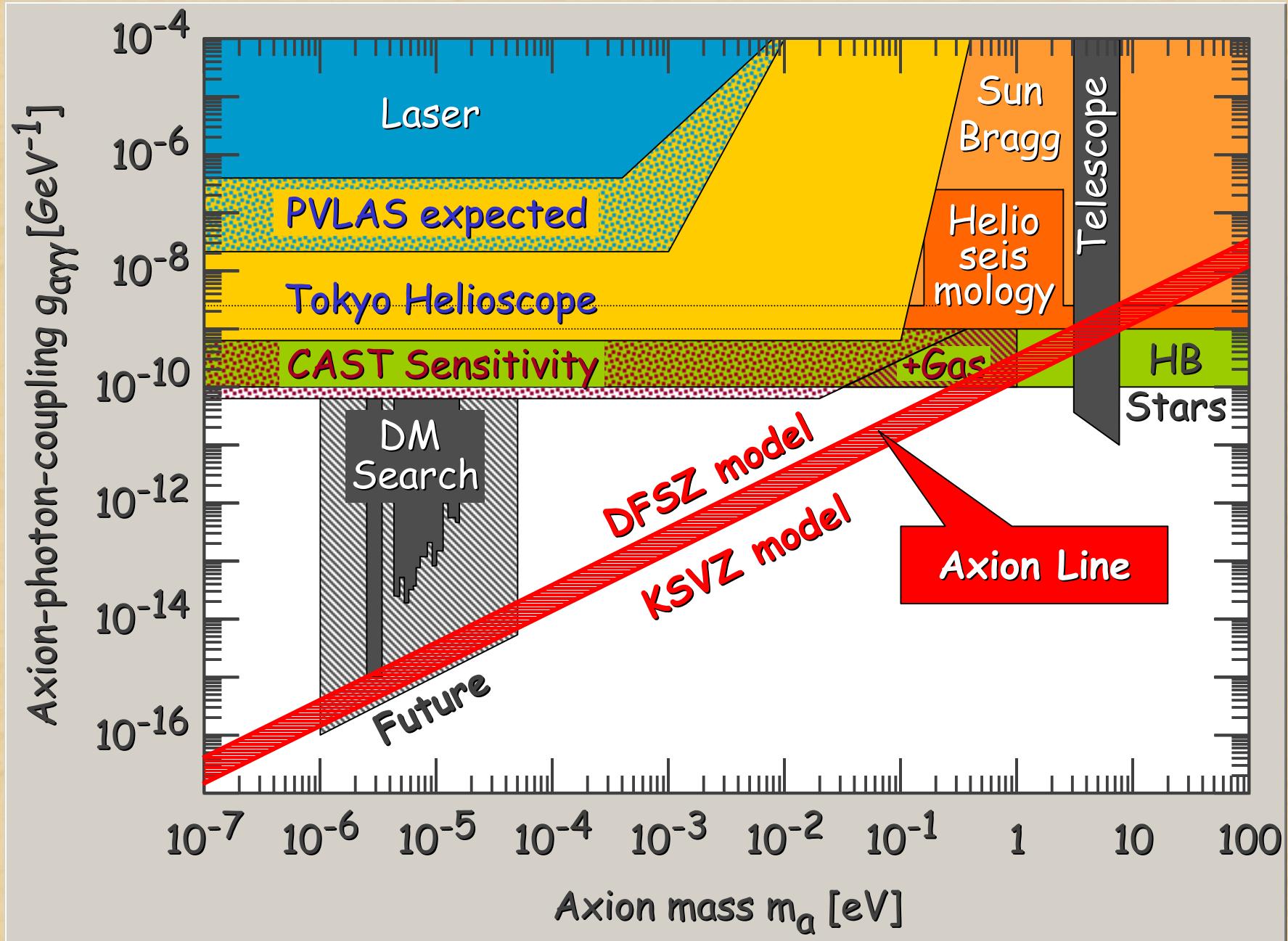


Abrixas x-ray satellite, failed shortly after launch in 1999



One spare x-ray mirror available from Zeiss, has been tested at Panther facility of MPE Garching

# Limits on Axion-Photon-Coupling



# Axion Software



AXION SPATIAL IMAGING



ENTER

AXION INTERNET



AXION



j-axion



LE DICO AXION



consultancy

system design

manufacture

installation and support

home



Axion Technologies  
<http://www.AxionTech.com>



A B&P Company

# Limits on Axion-Photon-Coupling

